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Detector Technology: DCS → MaRIE

& the ps, GHz, TB challenges

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K. K. Kwiatkowski, S.-N. Luo, and C. L. Morris*

Los Alamos National Laboratory

DCS workshop, Jan. 19-20, 2012

Detector technology: DCS to MARIE and the ps, GHz, TB challenges

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Abstract

Coherent hard X-rays from FEL with energies above 10 keV, together with a 20-GeV electron beam and an 800-MeV proton beam, are being proposed for imaging of transient phenomena involving actinides in MPDH. Detector technology, like the light and charged particle sources and imaging systems, is a basic component of the facility. Compared with detections of energetic electrons and protons, detection of hard X-rays is more involved because of the need for photoelectric conversion.

The requirements of MPDH X-ray detection can be summarized as follows. Image frame time or gating time is about one ps or shorter. Frame time is the time of signal integration for each frame of image. Time resolution is about three hundred ps or better. This is the time in-between frames. The total number of frames can be more than three thousands for a continuous movie that lasts for one microsec per event. The sample size is limited to about 100 μm for Pu-like high-Z samples due to X-ray attenuation. Larger samples have to use charged particles, and in particular proton beams (see below). The spatial resolution is on the order 100 nm or less. The state-of-the art in resolution of X-ray imaging is less than 10 nm. The dynamic range of the detector covers single photon counting to about one million photons per pixel. Combined background and electronic noises therefore must be essentially about one electron or less in order to count individual photons. The detection efficiency needs to exceed 50% for 50 keV X-ray photons.

Correspondingly, the MPDH X-ray detectors (imaging cameras) need to meet the following specifications. One ps gating time could be achieved through the proposed sub-ps XFEL pulses. The fastest scintillators can respond within about 30 ps. Although the overall system response is about 1 ns or longer. The fastest semiconductors can, in principle, achieve similar response time as the fastest scintillators, depending on the detector size, operating temperature and wavelength of the X-ray photons. X-ray detection and signal recording must happen within 300 ps. Such a rapid signal recording may require on-board memory to eliminate the dead time due to signal transmission. Acquiring more

than three frames within 1 ns, or a frame rate above 3 billion frame per second for at least a microsecond, has not been demonstrated before. For Fraunhofer diffractive imaging, the detector voxel (For high detection efficiencies at 50 keV, the third dimension of a conventional 'pixel' is now comparable to the other two dimensions, therefore 'voxel' is more appropriate) size is about the size of the sample, or about several hundred μm for MPDH. The overall detector size is about one thousand times the pixel size per dimension, determined by the ratio of the sample size to spatial resolution. A dynamic range of 10^6 requires at least 20 bits of recording depth. In short, although the basic mechanisms on how to detect hard X-rays are well understood and various aspects of detector specifications can be met using some existing technologies, the overall technological challenges to meet all of the MPDH requirements in a single detector (camera) are unprecedented and need further development.

A dedicated research program is recommended. Such an effort can take on several directions and each in several phases. Initially, MPDH can take advantage of the on-going pRad effort on a second-generation fast (50 ns) multi-frame imager. It is expected that at 10 keV X-ray energy, the existing 100 μm thick Si sensor can be used as a fast high-efficiency (above 50%) direct-detection imager. Later on, new generations of detectors based on high electron mobility and higher Z materials, such as GaAs or InSb, can be developed. For example, absorption efficiency above 50% for 50 keV photons can be readily achieved using a layer thickness of about 100 μm of InSb. Another direction of development could be on architecture of X-ray detectors, which can process and store $\sim 1.2 \times 10^{19}$ byte of data per second = 3×10^9 (frame rate) $\times 10^6$ (number of pixels) $\times 10^6$ (dynamic range)/ 256 (8 bit per byte) for at least 1 μs (or ~ 10 TB per event). Significant involvements from micro-fabrication industry (ASIC technologies), academia, and possibly other DoE laboratories may be necessary to address the challenges.

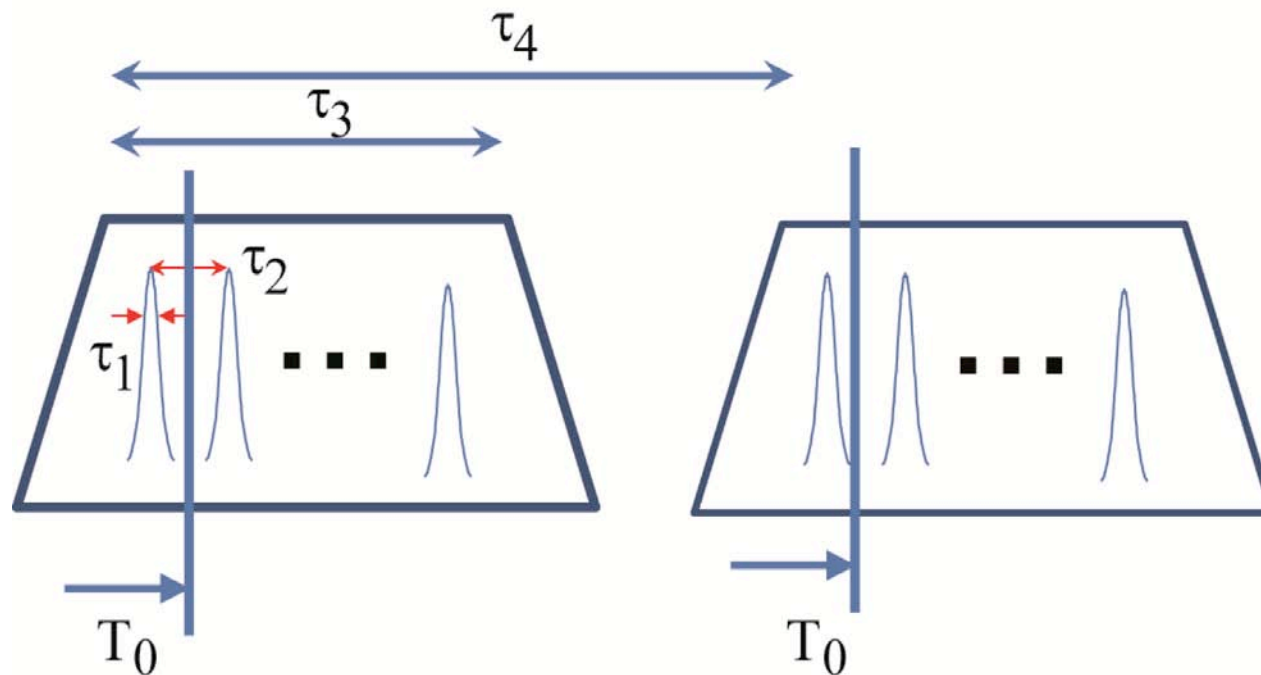
Charged particle-based radiography and tomography methods can share the detector technology with X-ray methods. X-ray imaging methods provide a bottom-up tool to MPDH. Their main advantage is very fine spatial resolution (\sim a few nm). They are however limited to very thin sample sizes (\sim mm for low-Z samples and sub-mm for high-Z samples) due to attenuation of X-rays. A second limitation is the large sample-to-detector distance if Fraunhofer diffraction has to be used. The 20 GeV electron beam and 800 MeV pRad and tomography provide a top-down tool to MPDH and can examine meter-scale objects. Compared with electron methods, proton methods are less sensitive to multiple scattering and more mature. Proposal to extend the spatial resolutions of proton tomography to 10 μm or less exists.

Besides the direct impact on the MPDH/MaRIE and other related programs of NNSA interest, the development can also benefit many scientific disciplines and communities at large; in particular, cosmology, medicine, homeland security, energy systems and material discovery. These additional benefits to other field may be justifications for funding outside DoE/NNSA.

Outline

- **MPDH time and spatial scales**
- **Detector requirements**
- **Detectors today**
- **R&D activities on detectors**
- **R&D needs for MPDH detectors**
 - The ps challenge
 - The GHz challenge
 - The TB challenge

Experimental time scales for MPDH



$\tau_1 \sim 1$ ps (laser pulse/gating)

$\tau_2 \sim 300$ ps (3 GHz or faster)

$\tau_3 \sim 1$ μ s

$\tau_4 \sim 10$ ms

Light source/Detector

Detector Technology

Detector Technology / cost

Facility cost

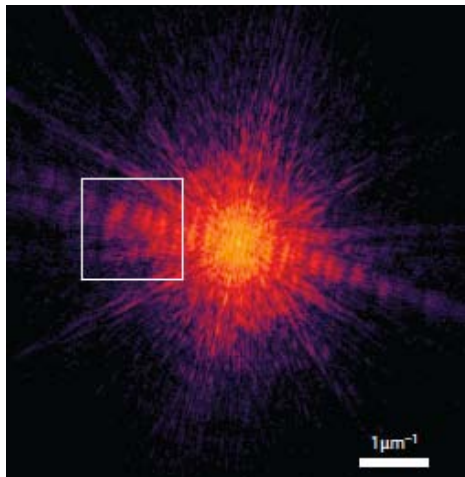
Experimental spatial scales

■ MPDH requirements

- Resolution $\sim 0.1 - 1 \mu\text{m}$
- Sample size $\sim 100 \mu\text{m}$ for actinides

■ State-of-the-art

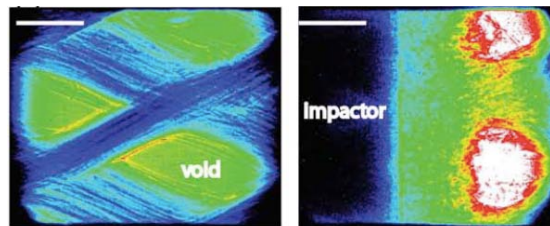
CDI



0.15 μm (resolution); 15 μm

Abbey et al (2011)

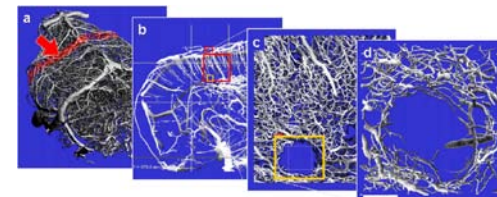
Dynamic phase contrast



3 μm (resolution); 2 mm

Luo et al (2011)

Synchrotron μCT

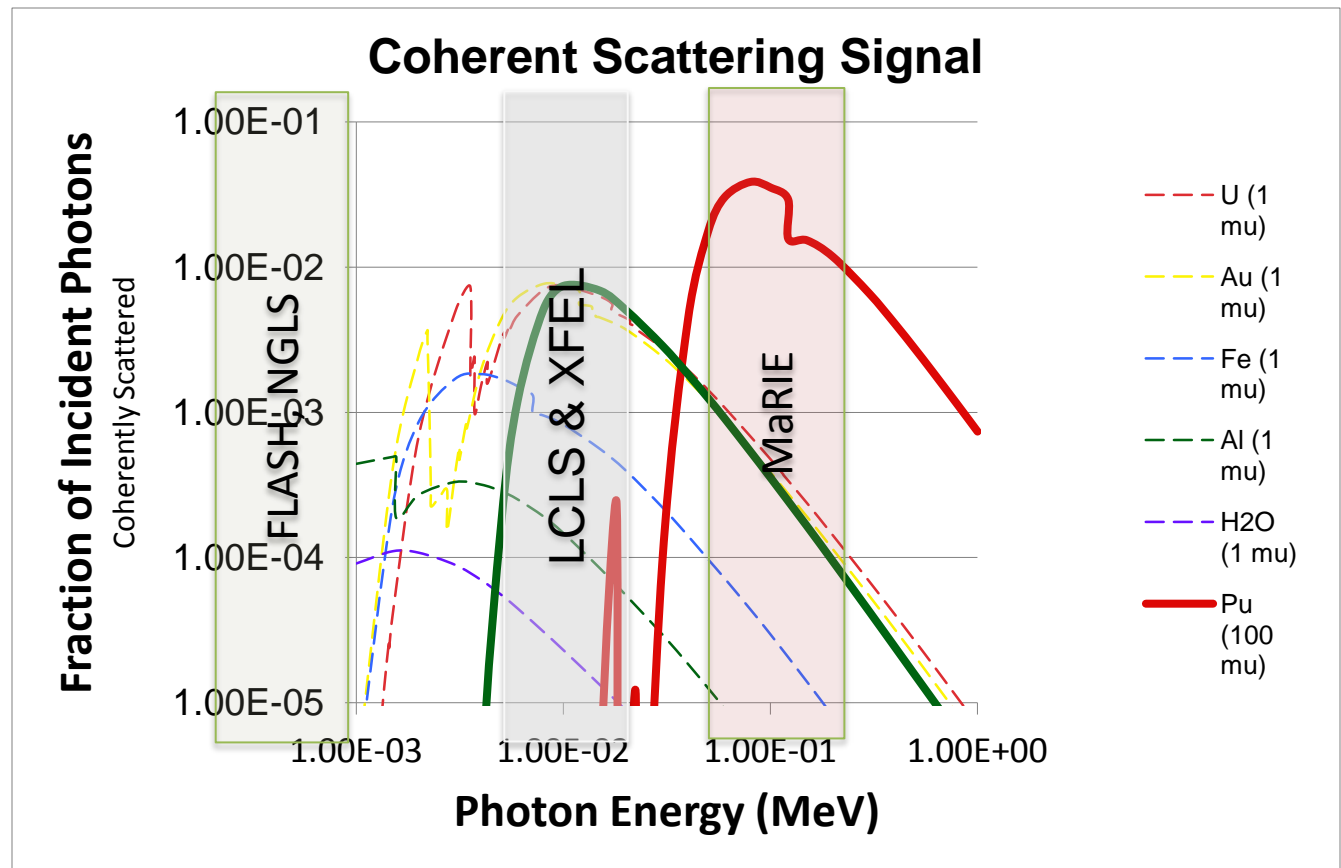


1 μm (resolution); 1 mm³

Heinzer et al (2006); Ritman (2011)

<10% flux available for coherent imaging

➡ (> 50% efficiency for detection)

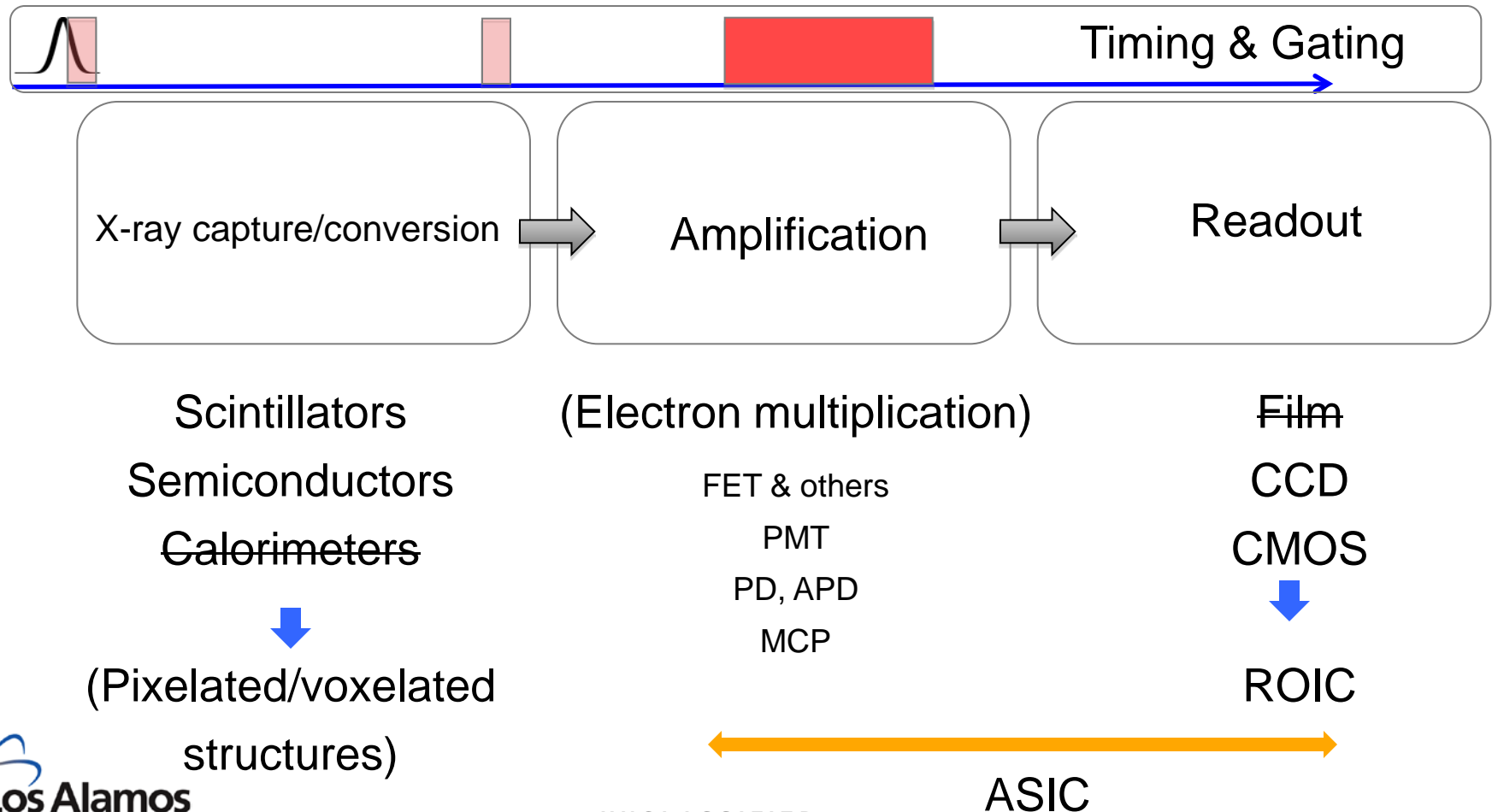


MPDH detector requirements

Parameters	MaRIE values	Existing Capability
X-ray capture (Z)	\geq Sn (50)	Si(14) - Hg (80)
X-ray energy	10 - 50 keV	1 to > 100 keV
Energy resolution	< 0.4 keV	< 0.4 keV
DQE @ 10 keV	> 50%	> 50%
DQE @ 50 keV	> 50%	< 20%
Operating temperature	\leq 300 K	\leq 300 K
Readout noise	< 1 e ⁻	< 10 e ⁻
Gain	1 - 100	1- 100
Dynamic range	\geq 20 bit	14 to 31 bit
Pixel/voxel size	50 to 3000 μ m	30 to 3000 μ m
Fill factor	> 90 %	> 90%
Gating time	\leq 1 ps	\geq 300 ps
Frame rate	3 to 10 GHz	\sim 1 MHz
Number of frames	50 to 10,000	\geq 10
Lifetime	> 100 hr	> 100 hr

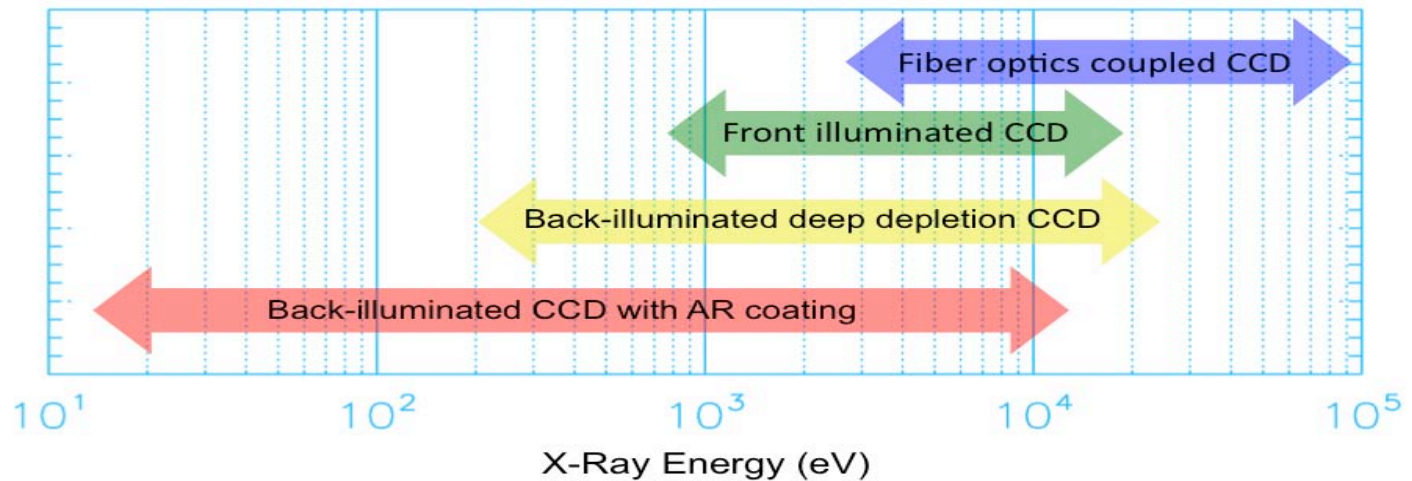
XFEL source

Building-blocks of X-ray detectors

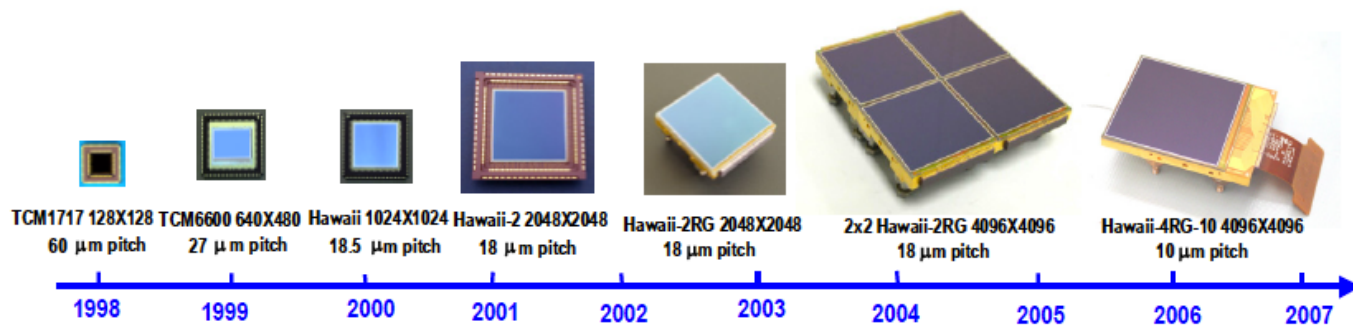


Commercial X-ray detection

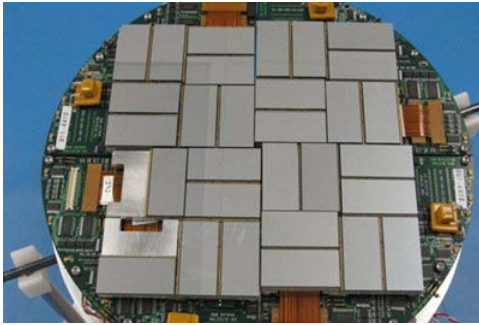
CCD



CMOS

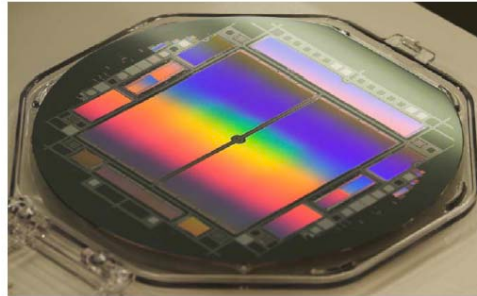


Application specific X-ray detection



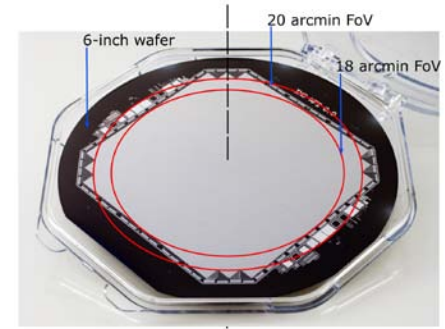
CS-PAD

Synchrotron/XFEL



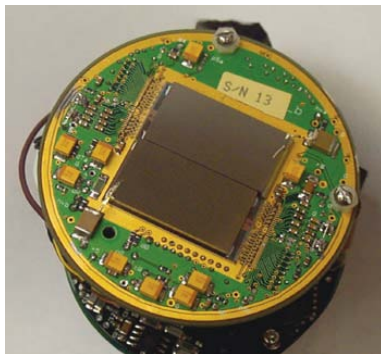
pnCCD

Synchrotron/XFEL/Astronomy



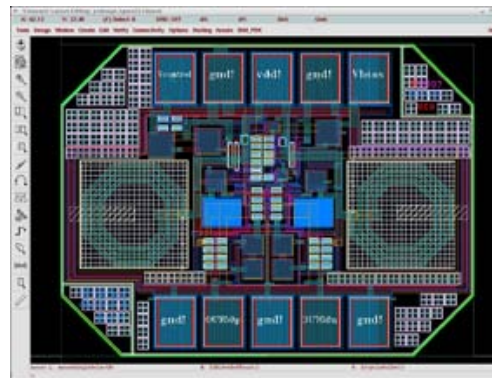
DEPFET

Astronomy/Synchrotron/XFEL



CZT detector

NIF



Large-area ps photodetector

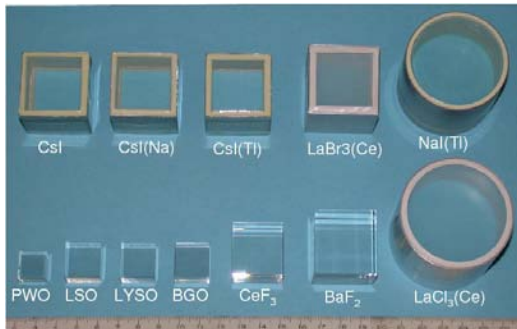
HEP



CsI(Tl) array

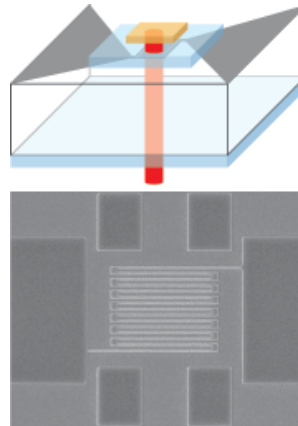
Commercial (RMD)

R&D activities in small groups (*small samples*)



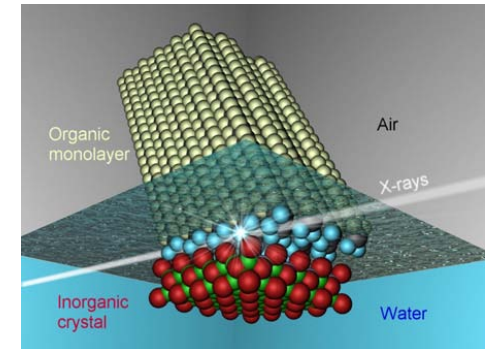
New scintillators

(Zhu et al.)



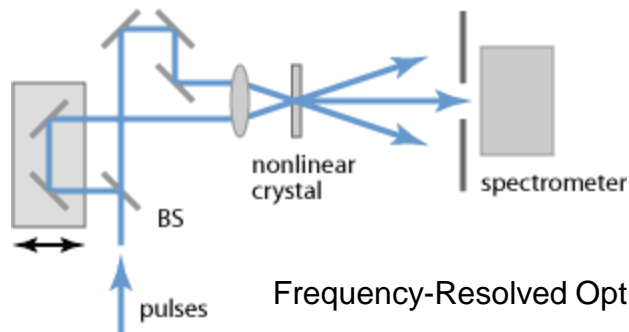
SNSPD

(Gol'tsman et al)



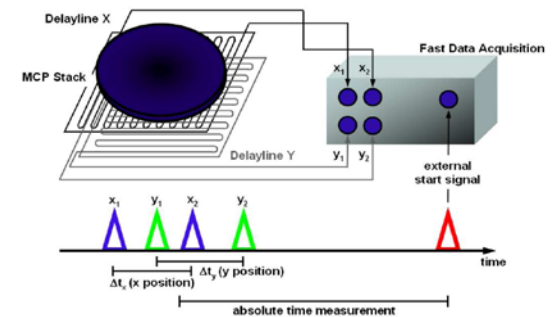
Molecular detectors

(Kemtko et al; Tahara et al)



Frequency-Resolved Optical Gating

(Trebino et al.)



Delayline detectors

(<http://www.surface-concept.de/>)

R&D Challenges for MPDH Detectors

■ The “ps challenge”

- High-efficiency (>50%) for 50 keV X-rays
- fast time response (~ 300 ps or less)
- Using multiple imaging systems can relax the time requirement by xN , (N = the number of imaging systems)

■ The “GHz challenge”

- Sub-ns (~ 3 GHz or faster) frame rate X-ray cameras
- Movie length, 50 to 10,000 frames
- Using multiple imaging systems can relax the frame rate and number of frame requirements by xN , (N = the number of imaging systems)

■ The “TB challenge”

- High data rate, 1.3×10^{19} byte of data per second = 3×10^9 (frame per second) $\times 10^6$ (number of pixels) $\times 10^6$ (dynamic range) / 256 (8 bit per byte)
- Large amount of data, up to 10 TB per $1 \mu\text{s}$ event .
- Using multiple imaging systems can relax the data rate and the amount of data requirements by xN , (N = the number of imaging systems)

Semiconductor path to ps & GHz (I)

■ On-going development

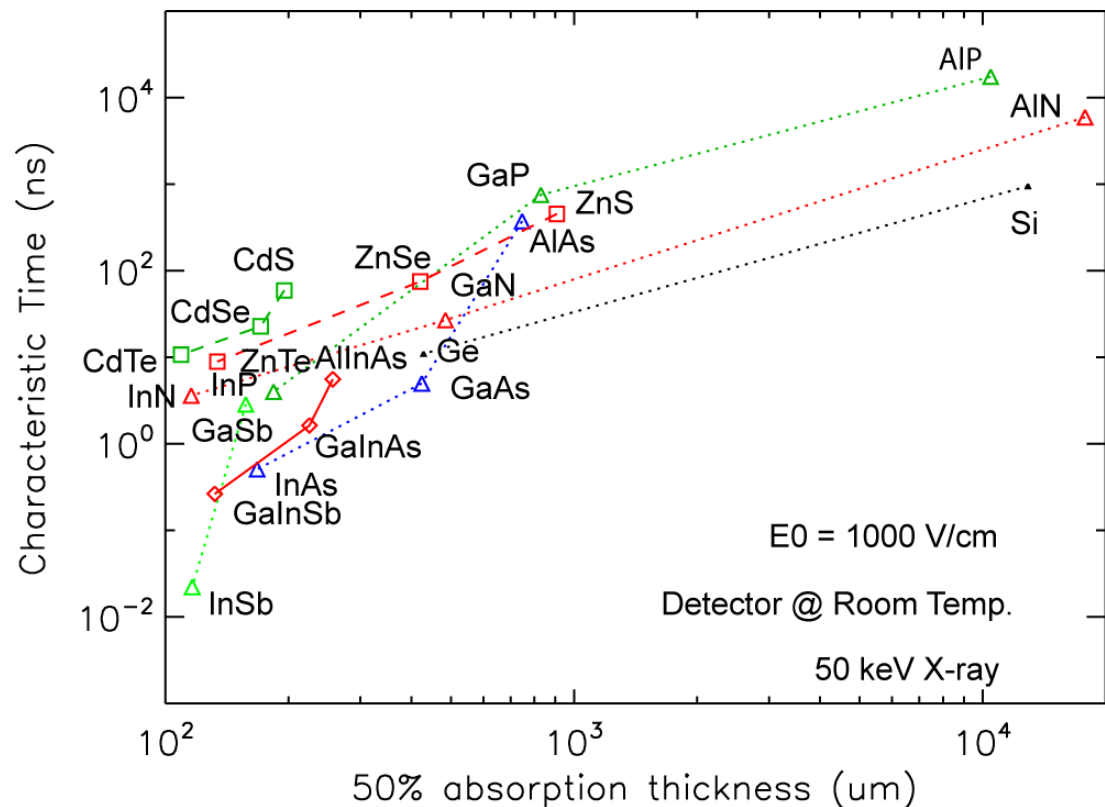
- Second Gen. Imager (Kwiatkowski, Luo et al.)

Design Paramters	1st Gen. Imager	2nd Gen. Imager
Capture material	Si	100 μm thick Si(14)
DQE @ 415 nm	85%	>90%
Operating temperature	300 K	300 K
Readout noise	100 e^-	$\sim 37 \text{ e}^-$
Saturation level/well depth	$> 200 \text{ ke}^-$	$\sim 150 \text{ ke}^-$
Pixel pitch	26 μm	40 μm
eff. Dynamic range	11.4 bit	12 bit
Pixel/voxel size	50 to 3000 μm	30 to 3000 μm
Imaging array size	720×720	1024×1024
Chip dimensions	$21 \times 22 \text{ mm}^2$	$\sim 47 \times 49 \text{ mm}^2$
Optical Fill factor	$\sim 100 \%$	$\sim 100\%$
Min. Integration time	150 ns	50 ns
Gating time	$\leq 1 \text{ ps}$	$\geq 300 \text{ ps}$
Max. Frame rate	1/350 GHz	1/150 GHz
Number of frames	3	10

Semiconductor path to ps & GHz (II)

Future development

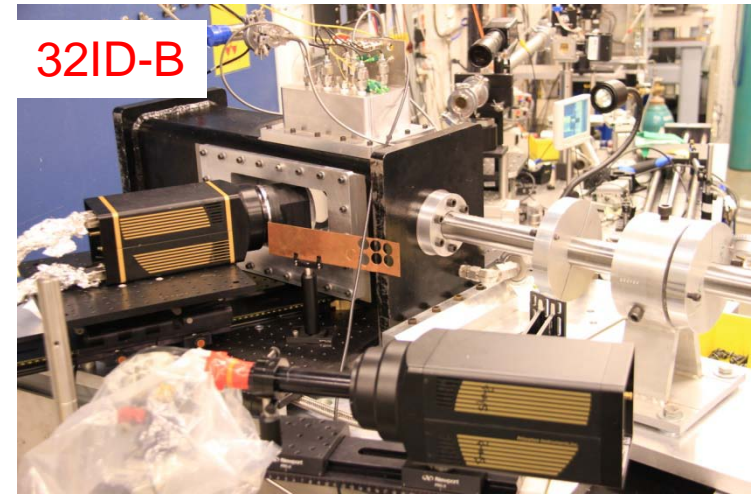
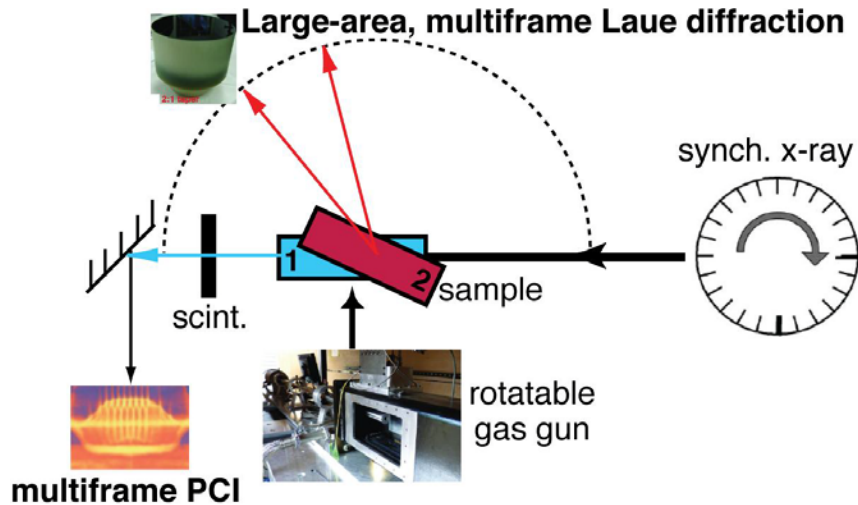
- Maximizing electron mobility
Lower temperature
Higher electrical bias
- Ultimate “drift” limit
 $\sim 10^8$ cm/s?



Some detector development for APS shock experiments

S. N. Luo, K. Kwiatkowski, K. Fezzaa (APS), B. Jensen, D. Hooks, Z. Wang, and C. Barnes

First dynamic ultrafast synchrotron x-ray PCI and Laue diffraction shock experiments at Advanced Photon Source (APS)



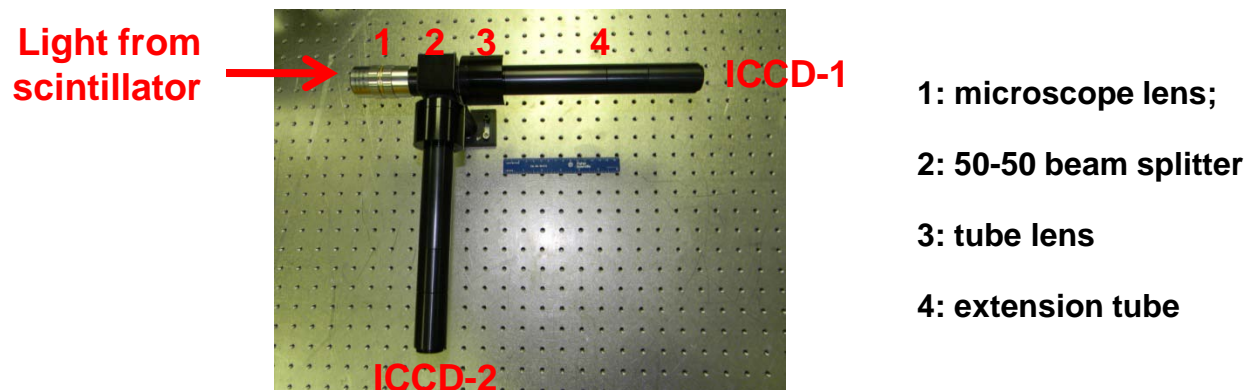
■ Highly successful dynamic measurements with a single, 60-ps, X-ray pulse at APS.

- *Established use of 0.5" gas gun (up to ~1 km/s for 4-10 g projectiles) at beamline 32ID-B. 33 shots were fired; turnaround time was 1-2 hours.*
- *Established dynamic phase contrast imaging (PCI) capability: first-ever, ultrafast (<100 ps), high spatial resolution (~3 μm), PCI measurements on representative materials and processes during dynamic loading. (The pulse separation was about 153 ns.)*
- *Preliminary ultrafast Laue diffraction of shocked single crystals (Fe) promises future success in revealing lattice changes during dynamic loading.*
- *Testing of a 3-frame Si-CMOS camera: promising for shock movies.*

Development of multiframe detector capability

■ If not photon-limited: optical beam splitter-multiplexing ICCD scheme

- LANL APS team is building a two-frame ICCD camera system.
- Commercial 8- and 16-frame multiplexing ICCD camera available.

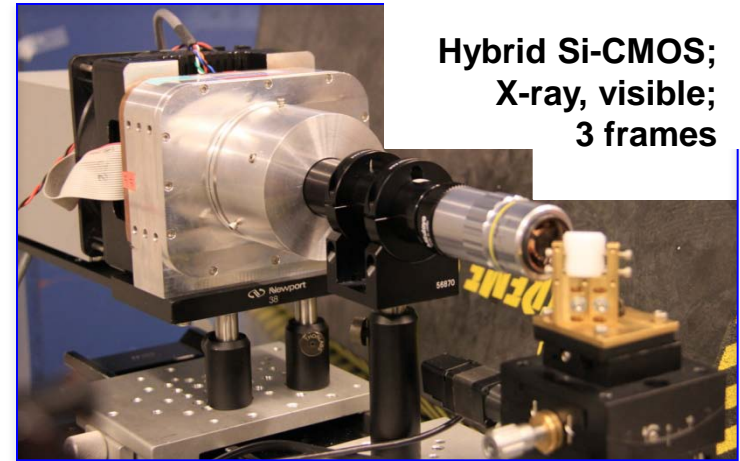


■ If photon limited: no beam splitting, onboard storage

- Two-frame single ICCD (500 ns frame separation) – limited use.
- Photosensor (Si)-CMOS cameras, 100-300 ns frame separation, 10+ frames – “ultimate” solution.
- Si-CMOS framing camera examples: Cornell, LANL (state of the art). Single frame, single-photon counting, Pilatus-type cameras Si-CMOS cameras not appropriate.

LANL Si-CMOS camera

- Princeton Instruments PI-MAX, single-frame, intensified CCD (ICCD) camera was used in our recent dynamic experiments.
- *Preliminary test with an existing 3-frame hybrid Si-CMOS camera was promising.*
- Valuable knowledge for developing more advanced photosensor-CMOS cameras.



(Field of view is $\sim 1.8 \times 1.8$ mm²; undulator gap 26 mm)

